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WHIRLING ARM TESTS
ON THE EFFECT OF GROUND PROXIMITY
TO AN AIRPLANE WING

NACA Contract NA w 1275

M. E. Long 5-12-44

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WHIRLING ARM TESTS ON THE EFFECT OF GROUND PROXIMITY TO AN AIRPLANE WING

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Summary

This report gives the results of tests on a rectangular wing model with a 20 percent full span split flap, conducted on the whirling arm at the Daniel Guggenheim Airship Institute in Akron, Ohio. The effect of a ground board on the lift and pitching moment was measured. The ground board consisted of an inclined ramp rising up in the test channel to a level floor extending for some distance parallel to the model path. The path of the wing model with respect to the ground board accordingly represented with comparative exactness an airplane coming in for a landing. The ground clearances over the level portion of the board varied from .6 to 1.6 chord lengths.

Results are given in the standard dimensionless coefficients plotted versus angle of attack for a particular ground clearance.

The effect of the ground board is to increase the lift coefficient for a given angle of attack all the way up the stall. The magnitude of the increase varies both with the ground clearance and the angle of attack. The effect on the pitching moment coefficient is not so readily apparent due to experimental difficulties but, in general, the diving moment increases over the ground board. This effect is apparent principally at the high angles of attack. An exception to this affect occurs with flaps deflected at the lowest ground clearance (0.6 chords). Here the diving moment decreases over the ground board.

It may be emphasized here that the only results which may be used directly for numerical computations are those shown in Figures 7 and 8, which give

increments in the lift coefficient due to the presence of the ground board. The other curves are included only in order to show how Figures 7 and 8 were derived, and to facilitate critical evaluation of these results.

Introduction

The problem of determining the effect of ground proximity on air foils or airplane models has been approached in the past by two different methods, both of which were utilized in wind tunnel tests. In one method the ground is represented by a flat plane surface of considerable extent introduced into the air stream below the model. This is the simplest experimental approach but it is open to the objection that such a plate has a boundary layer adjacent to it due to the motion of the airstream over the plate. At small ground clearances the effect of this boundary layer may be considerable. Different suggestions have been advanced to overcome the difficulty occasioned by this boundary layer. Thus, one writer proposes the elimination of the boundary layer by alternately sucking away and blowing out air through slots in the surface of the ground board (reference 1). A second modification, originally proposed by Eiffel, is to use a belt moving parallel to the air stream as the ground board (reference 2). However, as far as is known, no test results have been reported by either of these investigators, and those tests that have been conducted over ground boards in wind tunnels are subject to the modifying action of the boundary layer. A second method consists in utilizing two identical models set up symmetrically about a plane of reflection parallel to the air stream. This theoretically results in neutralizing the cross flow which would result from a single model, giving an effect similar to that obtained under the presence of an actual surface in the air stream midway between the symmetrical models. Experimentally, this second approach to the problem presents difficulties. In the first place, it requires two models identical in shape. In the second place, the location of the models must be symmetrical about a plane parallel to the air flow, and changes in the position of one model must be accompanied by exactly opposite changes in the second. Accordingly, wind tunnel methods for determining ground effects are difficult and subject to sources of error.

The whirling arm at the Daniel Guggenheim Airship Institute (reference 3) seems to offer possibilities for conducting ground effect tests, since it is readily possible to build up a level floor in any particular section of the test channel to represent the ground board. Since the only motion of the air relative to the ground board is that due to the swirl in the test channel, the problem of the boundary layer over such a ground board would not exist. Further, it seems possible to represent all stages of the approach of the airplane to the landing position by suitably choosing the inclination of a sloping ramp leading up to the level ground board. The experimental difficulties that arise come from the necessity for measuring unsteady aerodynamic forces by means of some suspension mounted on the end of a more or less flexible rotating arm. This report gives results obtained by one particular type of model suspension and represents the first attempt at the use of the whirling arm for such a ground effect investigation.

Apparatus and Tests

Wing Model -

The model used in the present series of tests was a 60" x 10" rectangular wing of NACA 23012 air-foil section. A 20 per cent chord full span split flap was provided, the hinge being located at the 80 per cent chord line. The construction of the wing has been already described in some detail (reference 4).

Whirling Arm -

The whirling arm itself has also been described (reference 3). The wing model was suspended from an extension shaft attached to the end of the whirling arm proper. The relative dimensions and location of the model in the whirling arm test channel are shown in Fig. 1.

Ground Representation -

The ground plane was represented by a level plywood surface built up from the floor and extending for approximately 20 feet (24 chord lengths) in the direction of the model path. A sloping ramp connected the floor level of the test channel with this ground board. The slope of one to six was taken as representing reasonably closely the gliding angle of modern airplanes utilizing flaps.

Suspension System -

The aerodynamic forces on the wing were registered by diamond points scratching on a silvered glass slide. The details of the suspension by which the lift and pitching moment were registered more or less independently are given in reference 4. The suspension was designed to record drag forces in addition to the lift and pitching moment. However, it was found impractical to evaluate these records due to vibration forces of large amplitude. The records as scratched on the glass slides were enlarged and recorded on bromide paper for evaluation.

Swirl Correction -

One difficulty of utilizing the whirling arm for aerodynamic tests is the necessity of evaluating and correcting for the swirl which is set up by the drag of the arm itself, the suspension system, and the model being tested. In the present tests the velocity of the swirl was measured for approximately one half of the total number of test conditions by means of hot wire apparatus. The magnitude of the swirl was determined at several points in the free channel as well as over the ground board. The difference in the magnitudes was rarely greater than one foot per second so the average of the values at the different locations was used to correct the model velocity. The direction of the swirl was observed by means of a smoke wand. The flow in the region just below the model path was in general downward and towards the outer wall of the test channel. At any given point in the test channel the outward or cross flow decayed rather quickly following the immediate passage of the wing, so that this component was insignificant in the air just ahead of the model. The downwash in the test channel also smoothed out after the passage of the model, but at high lift coefficients a certain downward flow generally persisted even up to the return of the model. From observations on the directions of smoke plumes, and from hot wire velocity measurements, it is estimated that this directional effect in the swirl might cause an error of 1/2° in the effective angle of attack of the wing. It was difficult to observe the vertical direction of the swirl over the ground board, but it may be assumed that the level surface would restrict this downward flow rather effectively. Accordingly, the increase in the lift coefficient measured over the ground board may at high lift coefficients be in error by an amount equal to that due to an increase in the angle of attack of 1/2°, or approximately 0.05.

Ground Clearance Measurements -

The term ground clearance is defined for this report as the distance between the quarter chord point (from the leading edge and on the chord line of the wing) and the level ground board. These clearances were measured for each test since due to the elasticity of the whirling arm, change in the aerodynamic forces arising during successive tests caused a change in this clearance and necessitated continual adjustment of the model position. The measurements as taken can be only termed approximate, since successive measurements during the same test varied by 1/4" (.025 chord lengths). Chalk pencils with small tips were held up through holes in the ground board under each wing tip and the height of these pencils was measured after the trailing edge of the wing was seen to brush against them. This made possible determining and adjusting the spanwise attitude of the wing over the ground board as well as affording a measure of the height above the ground board of the lowest part of the wing section. The distances so measured were corrected for the difference in elevation between the lowest part of the wing and the quarter chord point.

Tests -

Tests were conducted at 0.6, 0.8, 1.2, and 1.6 chord lengths ground clearances at 0°, 45°, and 60° flap settings, at a test speed of approximately 80 miles an hour. The angle of attack was varied from -3° up to the stall, or until the wing at rest would not clear the ground plate.

Evaluation of Test Results -

Since the model and suspension system during the test runs were subjected to a centrifugal acceleration of 11g., it was necessary to determine what effect this had on the registration of the aerodynamic forces. Accordingly, calibrations of the suspension were carried out with an outward horizontal load applied to the wing equal to the centrifugal load which was acting during the test runs. (It was not practical to apply appropriate outward loads to each element of the suspension.) It was found that the calibration was unaffected by a change of ±10% in this centrifugal loading. To determine the effect of the centrifugal acceleration on the total suspension system, a weight equal in mass to the wing model was attached to the suspension. This weight was enclosed by a sheetmetal fairing, and test runs were made to determine the deflections of the various diamond points under the test speed. These records were used to establish zero lines from which the deflections due to aerodynamic loads were then measured.

Although the suspension was designed to record the lift, drag, and pitching moment independently, calibrations revealed interaction between the different elements of the system, and the actual evalutation of the lift record involved corrections determined from the drag and pitching moment records.

Results and Discussion

Coefficients and symbols -

The results are given in nondimensional coefficients

C_ℓ, lift coefficient $(L/\frac{\rho}{2}V_t^2 S)$

$\Delta C_\ell = C_\ell$ (over ground board) $- C_\ell$ (free air)

$C'm_{c/4}$, pitching moment coefficient about quarter-chord point $(M_{c/4}/\frac{\rho}{2}V_t^2\ S\ c)$

$\Delta C'm_{c/4} = C'm_{c/4}$ (over ground board) $- C'm_{c/4}$ (free air)

where

L is lift

$M_{c/4}$, pitching moment about the quarter-chord point.

ρ, air density in slugs/cu. ft.

V_t is test velocity in ft/sec, or model velocity relative to test channel minus velocity of swirl.

S is wing area in sq. ft.

c is wing chord in feet.

In addition,

α is angle of attack (degrees) and

h is the ground clearance, the distance of the quarter-chord point above the ground board.

Wind Tunnel Corrections -

No correction was made to the test data for the effect of the boundaries of the whirling arm test channel as preliminary computations indicated that this effect would be negligible. The exact solution would require computing the correction for the model in its off-center location in the 16' x 20' test channel, and for the wing over the ground board. Since the ground board does not extend completely across the channel, this latter case would be difficult of solution.

However, to facilitate a numerical estimation of the magnitude of the channel wall correction, the wing over the ground board could be considered as a model in a rectangular test section having a width equal to the width of the ground board and a height equal to the height of the ceiling above the board, and with one vertical side wall removed. If this test channel is then divided by a vertical center-line, the correction applicable to the outer half of the wing could be considered as that due to a closed rectangular channel, while the correction to apply to the inner half would be that due to a channel with horizontal boundaries but no vertical sides. These computations would then permit an approximate estimation of the magnitude of the correction necessary. Using the method given in reference 6, the closed rectangular section was found to cause an increase in the effective angle of attack $\Delta\alpha$ of 0.14°; at a C_ℓ value of 1.0, for the 1.6 chord ground clearance. Theodorsen (reference 7) has found that for a rectangular tunnel with horizontal boundaries but no vertical walls and a width-height ratio less than one the sign of the correction is negative. Accordingly it can safely be assumed that the net or average correction to the angle of attack would be less than 0.14° for a C_ℓ value of 1.0 for the given ground clearance. In the unrestricted section of the test channel the correction would be less than this, so that all channel wall corrections can be safely ignored.

Lift Coefficients Measured -

Fig. 2 is a comparison of lift coefficients measured in free air (8 chords ground clearance) compared with results of wind tunnel tests (reference 5). Apparently, the method of evaluating the test results does not include all the factors influencing the test records, for the C_ℓ vs. α curves for the different ground clearances should coincide for the free air condition. However, from the general nature of the curves in Fig. 2, it seems reasonable to assume that changes in the lift forces due to the presence of the ground board will be disclosed in their proper magnitude.

Figures 3, 4, 5, and 6 give lift coefficients measured in free air and over the ground board for the wing with 0°, 45°, and 60° flap setting, at 0.6, 0.8, 1.2, and 1.6 chords ground clearance respectively.

In Fig. 7, the increments of lift coefficient (ΔC_ℓ) due to the ground board are plotted for the different ground clearances, for each flap setting.

Fig. 8 shows the measured ΔC_ℓ values plotted for each flap setting, at particular angles of attack, as a function of ground clearance in chord lengths (h/c). For comparison, ΔC_ℓ values computed from wind tunnel test data (reference 6) are included.

Pitching Moment Coefficients Measured -

Fig. 9 is a comparison of pitching moment coefficients about the quarter-chord point measured in free air (8 chords ground clearance) for the different ground clearance settings of the wing on the whirling arm, compared with wind tunnel test data (reference 5). This comparison again makes evident that some factor influencing the test records has been overlooked in the evaluation procedure. It must be remarked also that the general nature of the curves derived from the whirling arm tests show considerable divergence from accepted pitching moment coefficient curves, especially for the 0° flap setting.

Figures 10, 11, 12, and 13 show pitching moment coefficients about the quarter-chord point ($C'm_{c/4}$) plotted versus angle of attack in degrees for the different flap angles at 0.6, 0.8, 1.2 and 1.6 chord ground clearances respectively.

Concluding Remarks

It is felt that the ΔC_ℓ values given in Figs. 7 and 8 are trustworthy, subject only to a possible error due to the change in effective angle of attack as the wing passes over the ground board. The probable maximum error in ΔC_ℓ is estimated at 0.05 for angles of attack in the order of 14° for the wing without flaps, or for equivalent C_ℓ values for the wing with flaps deflected.

However, even allowing for this possible error, the ΔC_{ℓ} values measured on the whirling arm are generally greater than those determined in the wind tunnel, particularly at the smaller ground clearances.

With respect to the pitching moment coefficients, results from these tests do not permit definite conclusions to be drawn. Thus Fig. 11 shows that $\Delta C'm_{c/4}$ changes in sign without any consistency as α increases. Fig. 10, however, shows that for 0.6 chord ground clearance, although $\Delta C'm_{c/4}$ is negative for 0° flap (at high values of α), it is positive for the 45° and 60° flap settings. This checks wind tunnel results reported in reference 6 for 0.5 chord ground clearance. Further, for 1.2 and 1.6 c ground clearance, for the 45° and 60° flap settings, the $\Delta C'm_{c/4}$ values, where significant, are negative. This would indicate that decrease in the diving moment coefficient is limited to the condition where the edge of the flap is extremely close to the ground board (0.6 or 0.5c clearance, flap deflected).

* * * * * *

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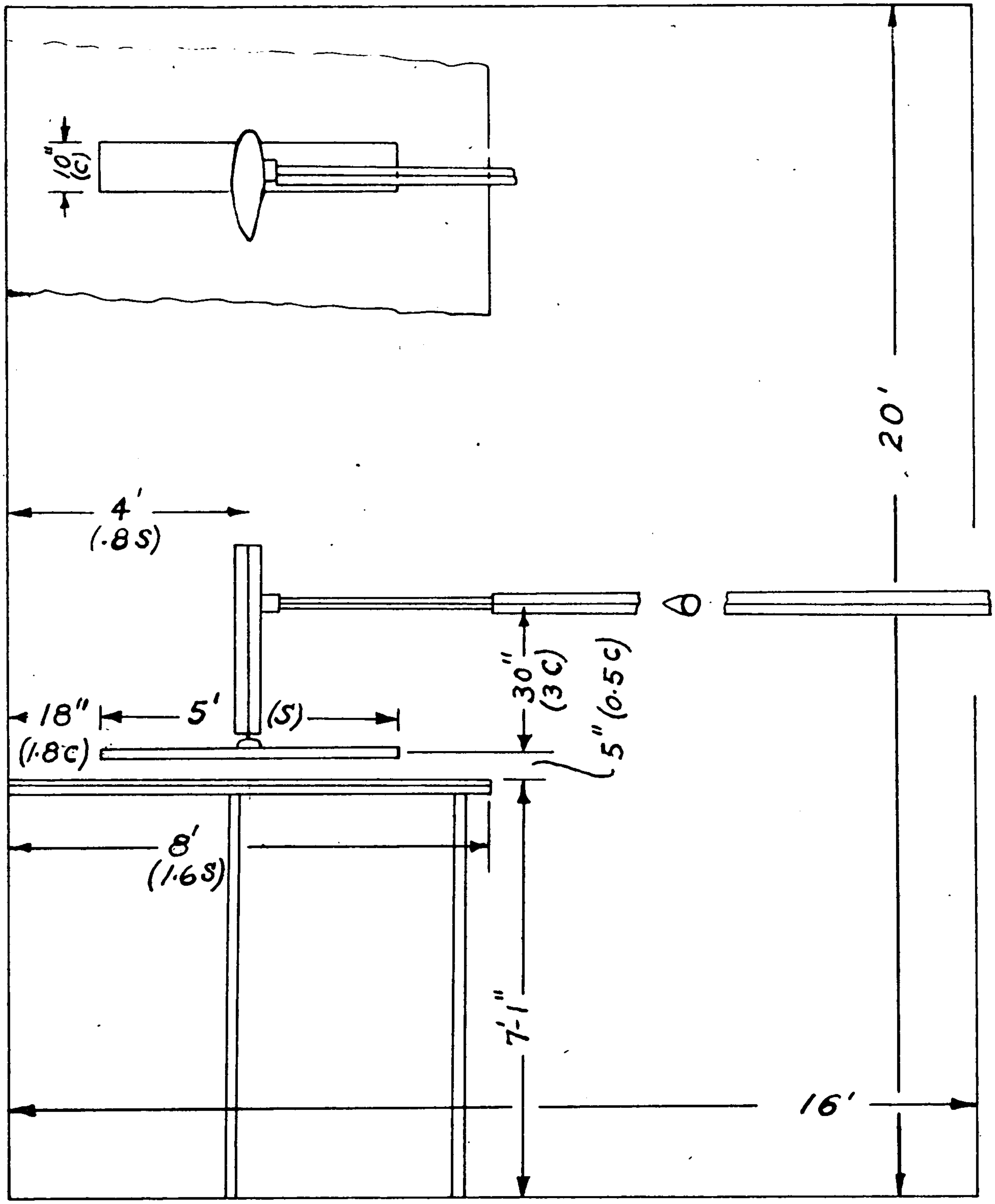

Figure I.

Diagram showing general dimensions of wing model installed on whirling arm, over ground board.

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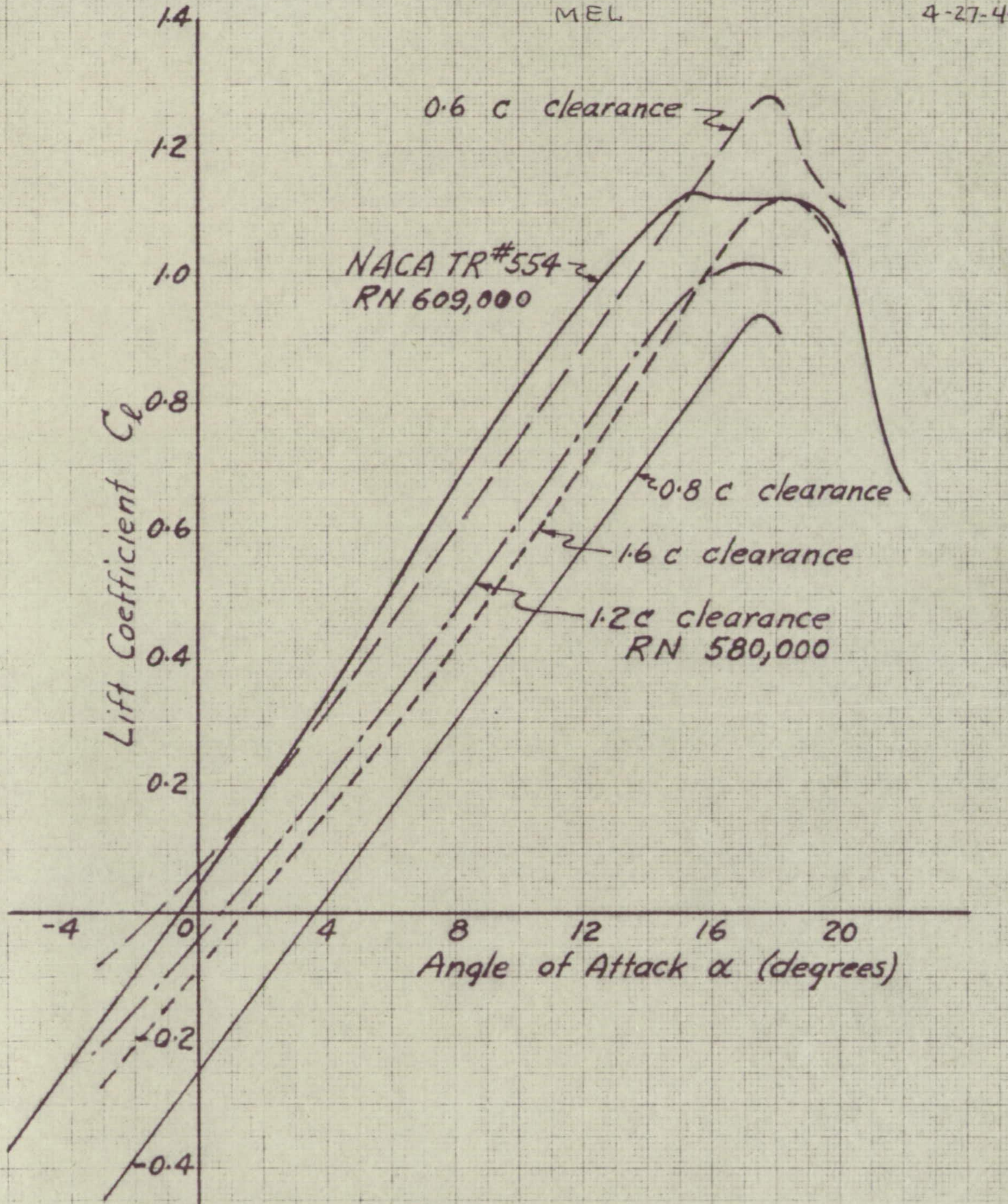

Fig. 2

Free Air Lift Coefficients measured for different ground clearance settings compared with data given in NACA Technical Report No. 554, Fig 5, p.3

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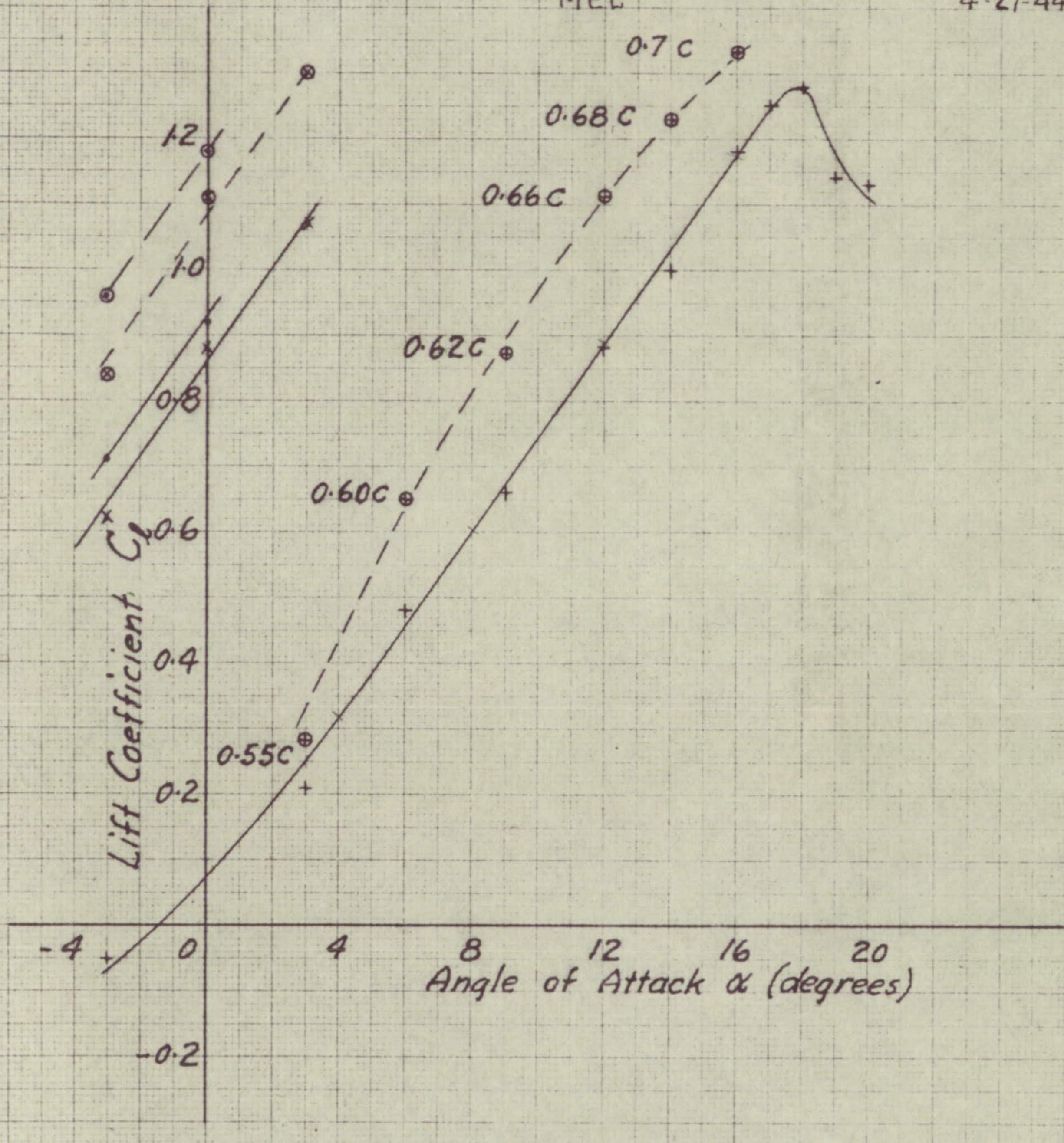

Fig. 3

Lift Coefficients measured in free air and over ground board for 0.6 chord ground clearance

0° flap setting, free air ——+——
over ground board – – ⊕ – –
45° flap setting, free air ——×——
over ground board – – ⊗ – –
60° flap setting, free air ——·——
over ground board – – ⊙ – –

Note: Ground clearances are 0.6 chord lengths except for 0° flap setting, where actual clearances are noted.

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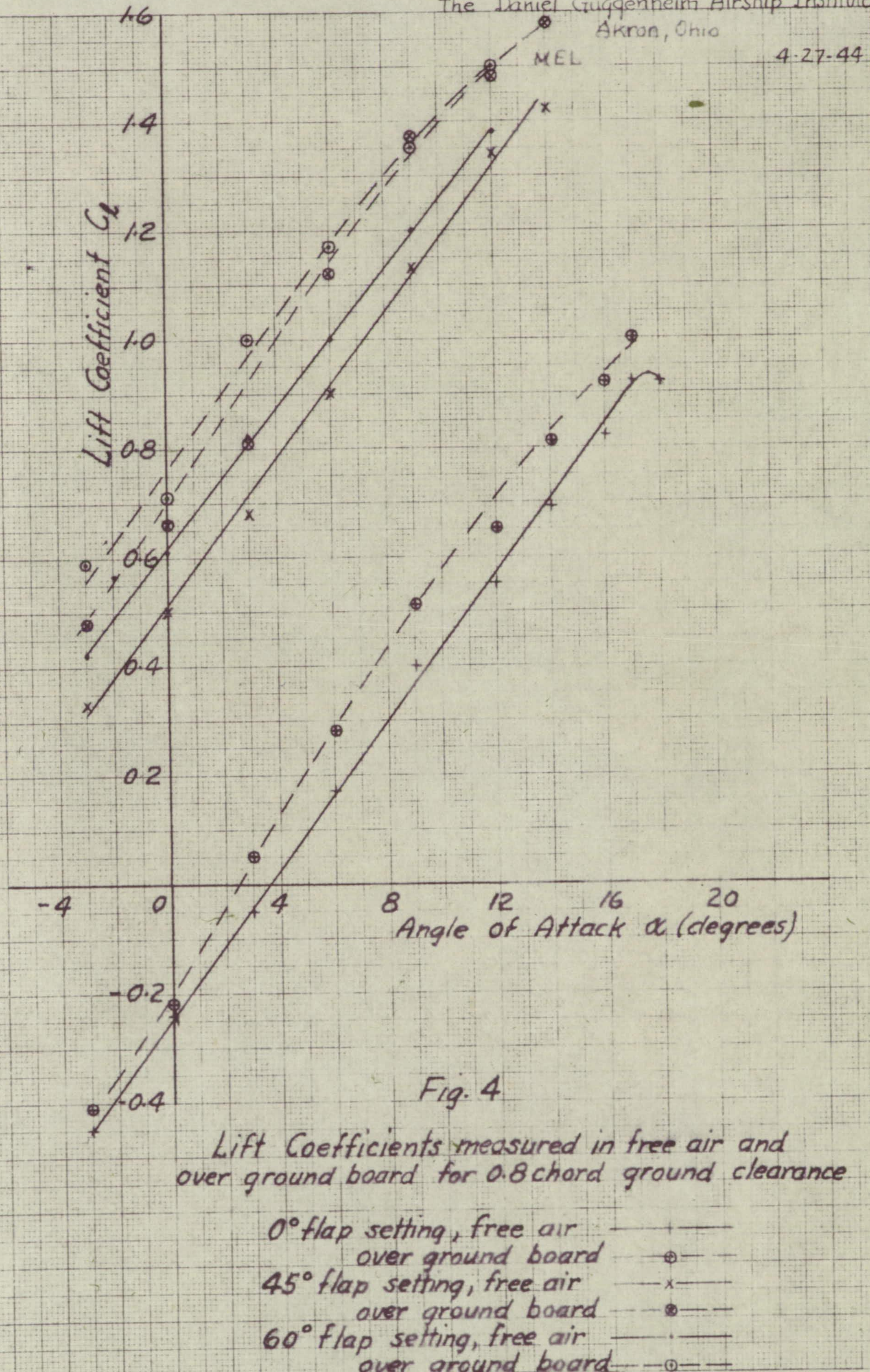

Fig. 4

Lift Coefficients measured in free air and over ground board for 0.8 chord ground clearance

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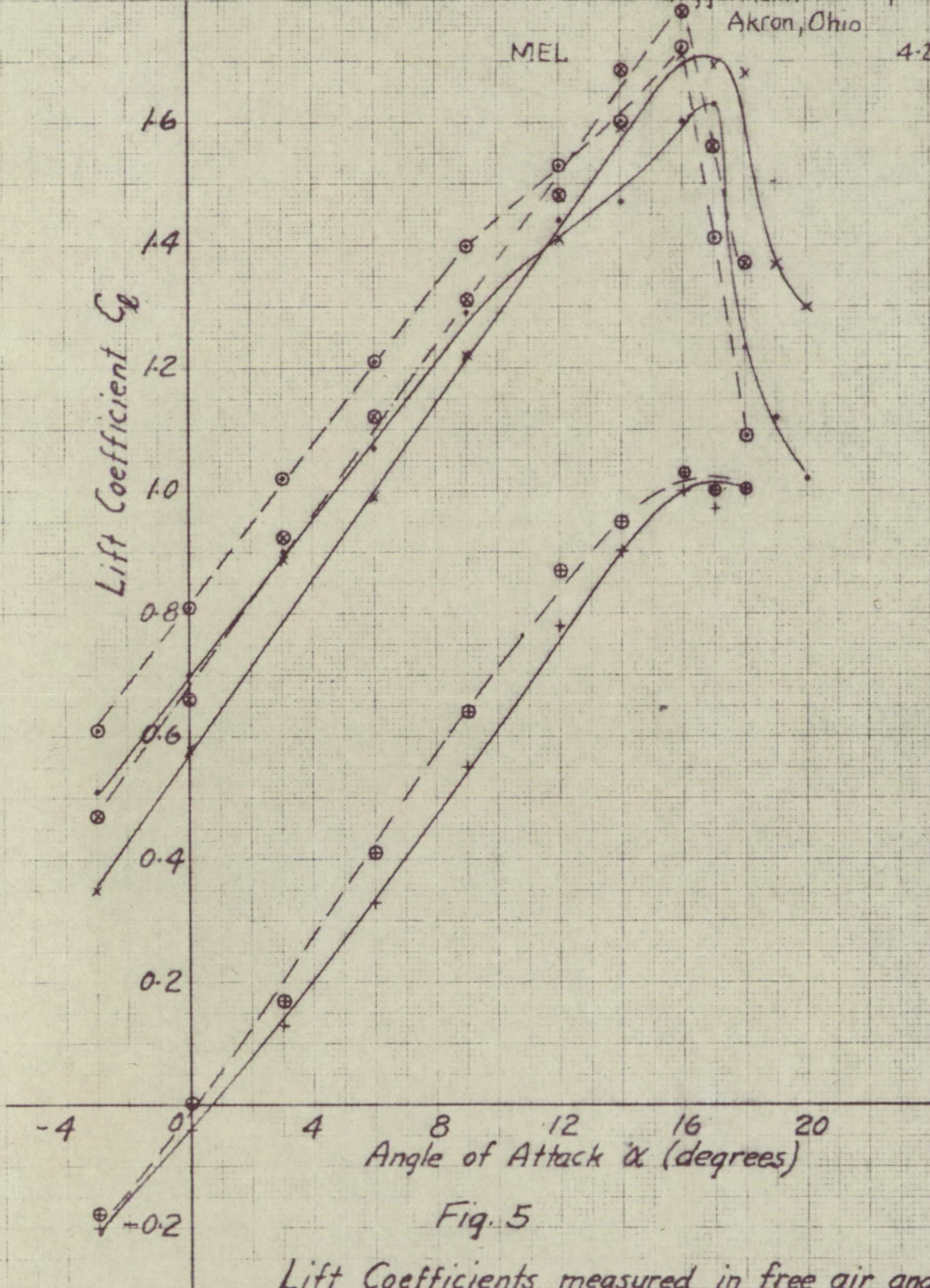

Fig. 5

Lift Coefficients measured in free air and over ground board for 1·2 chord ground clearance

0° flap setting, free air ——+——
over ground board — —⊕— —
45° flap setting, free air ——×——
over ground board — —⊗— —
60° flap setting, free air ——·——
over ground board — —⊙— —

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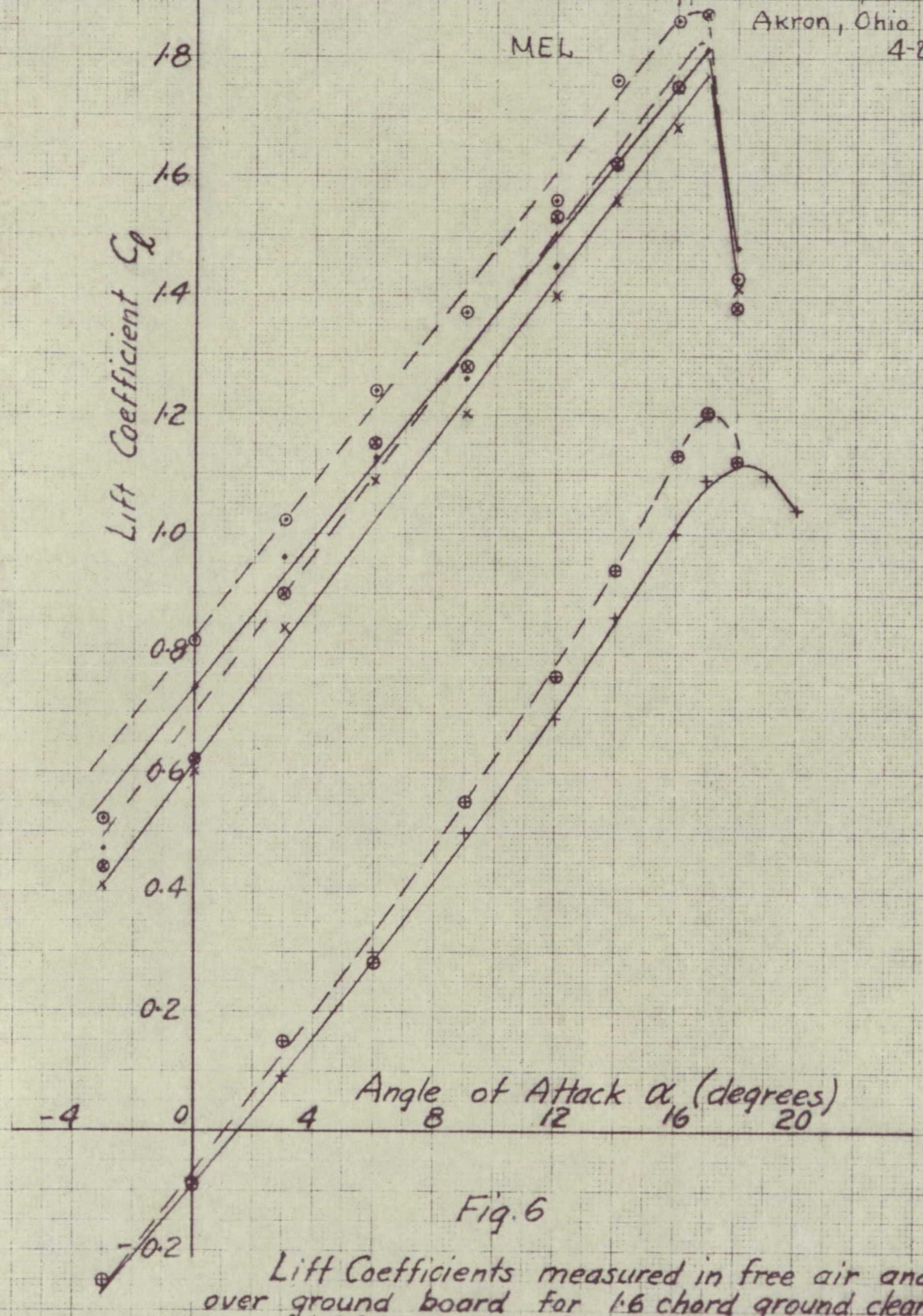

Fig. 6

Lift Coefficients measured in free air and over ground board for 1.6 chord ground clearance

0° flap setting, free air ——+——
over ground board — —⊕— —
45° flap setting, free air ——×——
over ground board — —⊗— —
60° flap setting, free air ——·——
over ground board — —●— —

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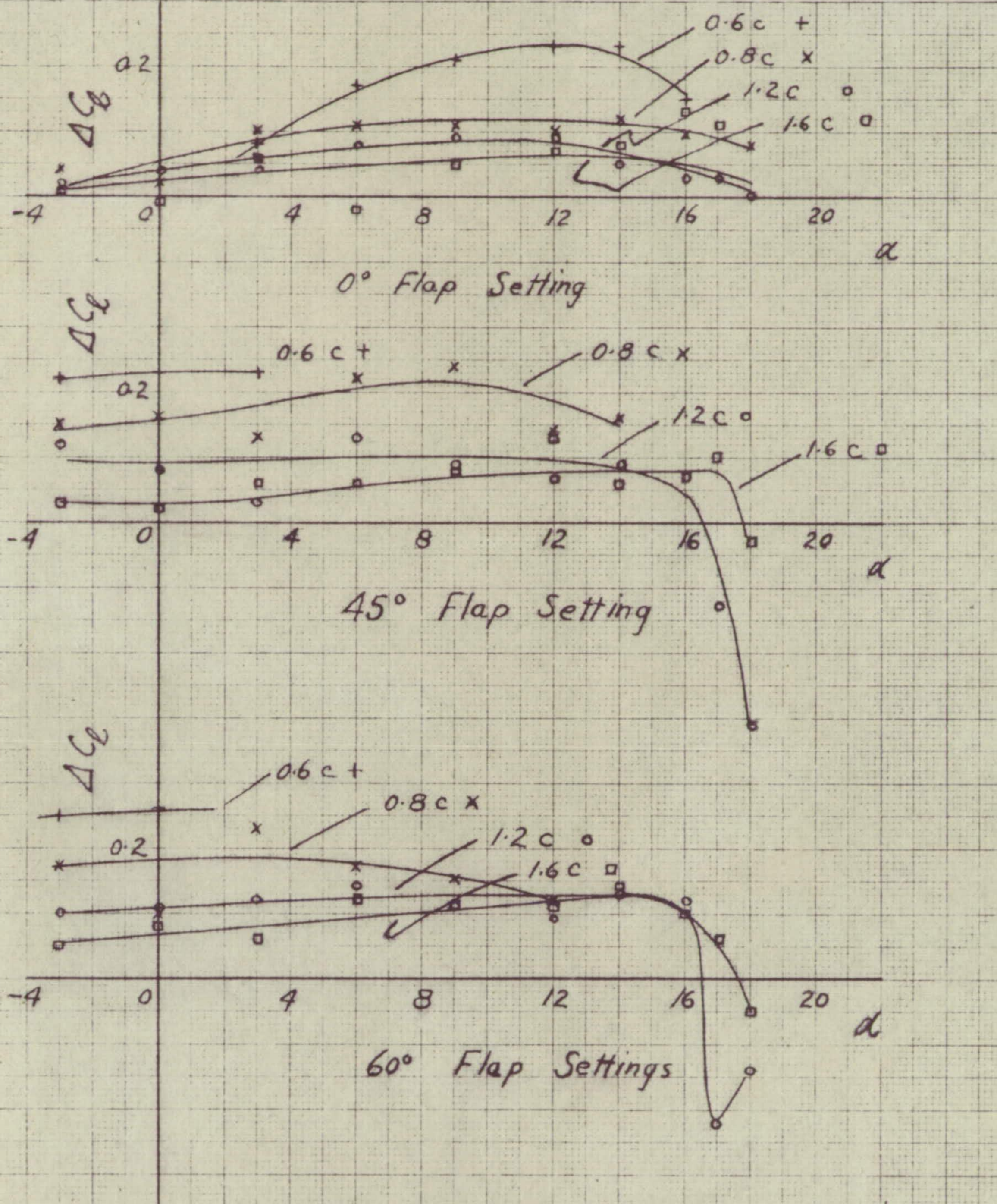

Fig. 7

ΔC_l plotted versus angle of attack α for different ground clearances and flap settings

$$\Delta C_l = C_{l_{\substack{ground\\board}}} - C_{l_{\substack{free\\air}}}$$

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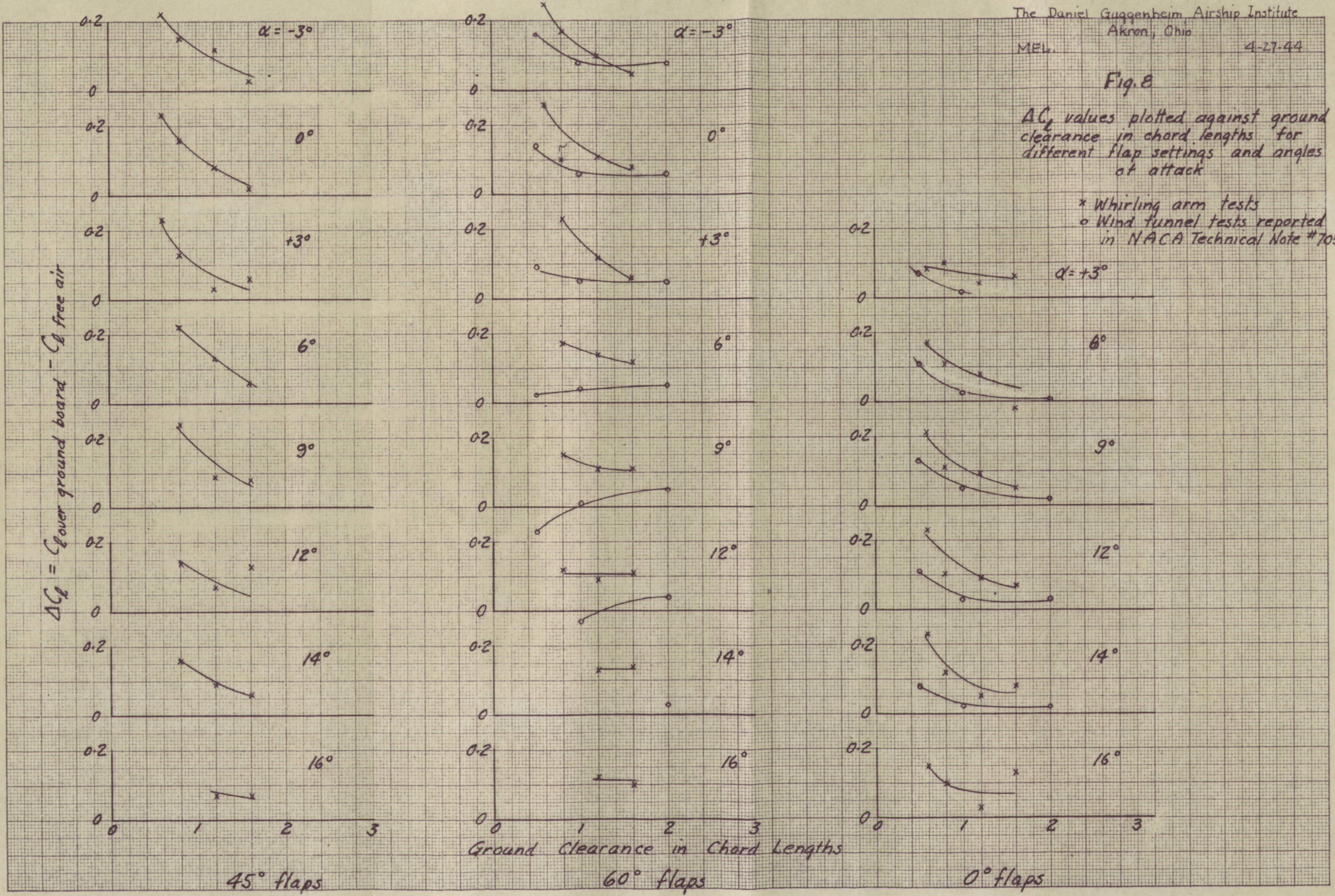
Fig. 8

ΔC_L values plotted against ground clearance in chord lengths for different flap settings and angles of attack

* Whirling arm tests
o Wind tunnel tests reported in N.A.C.A. Technical Note #705



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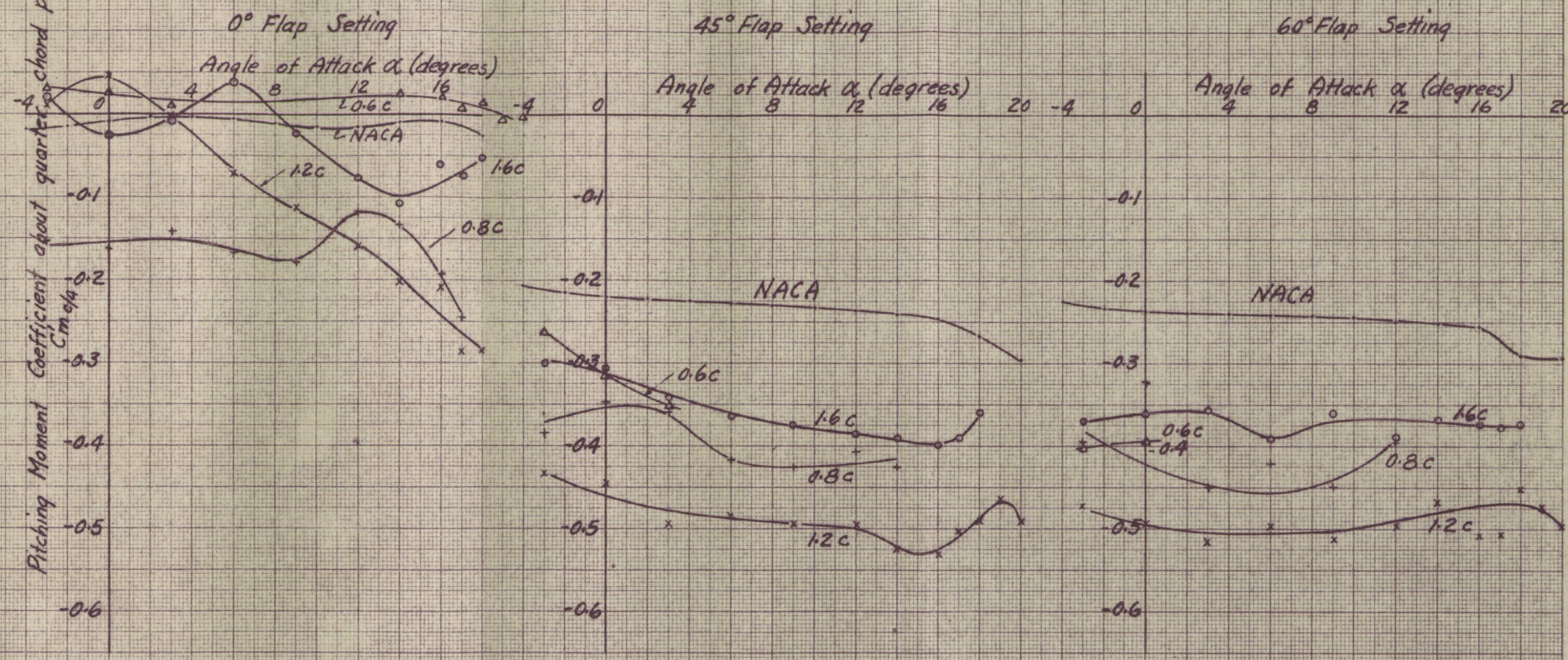

Fig. 9

Pitching moment coefficients about quarter-chord $C_{m\,c/4}$ measured in free air for different ground clearance settings compared with results given in NACA T.R. No. 554 for 23012 airfoil with .20c full span split flap

KEUFFEL & ESSER CO., N. Y. NO. 359-14L
Millimeters, 5 mm. lines accented, cm. lines heavy.
MADE IN U. S. A.

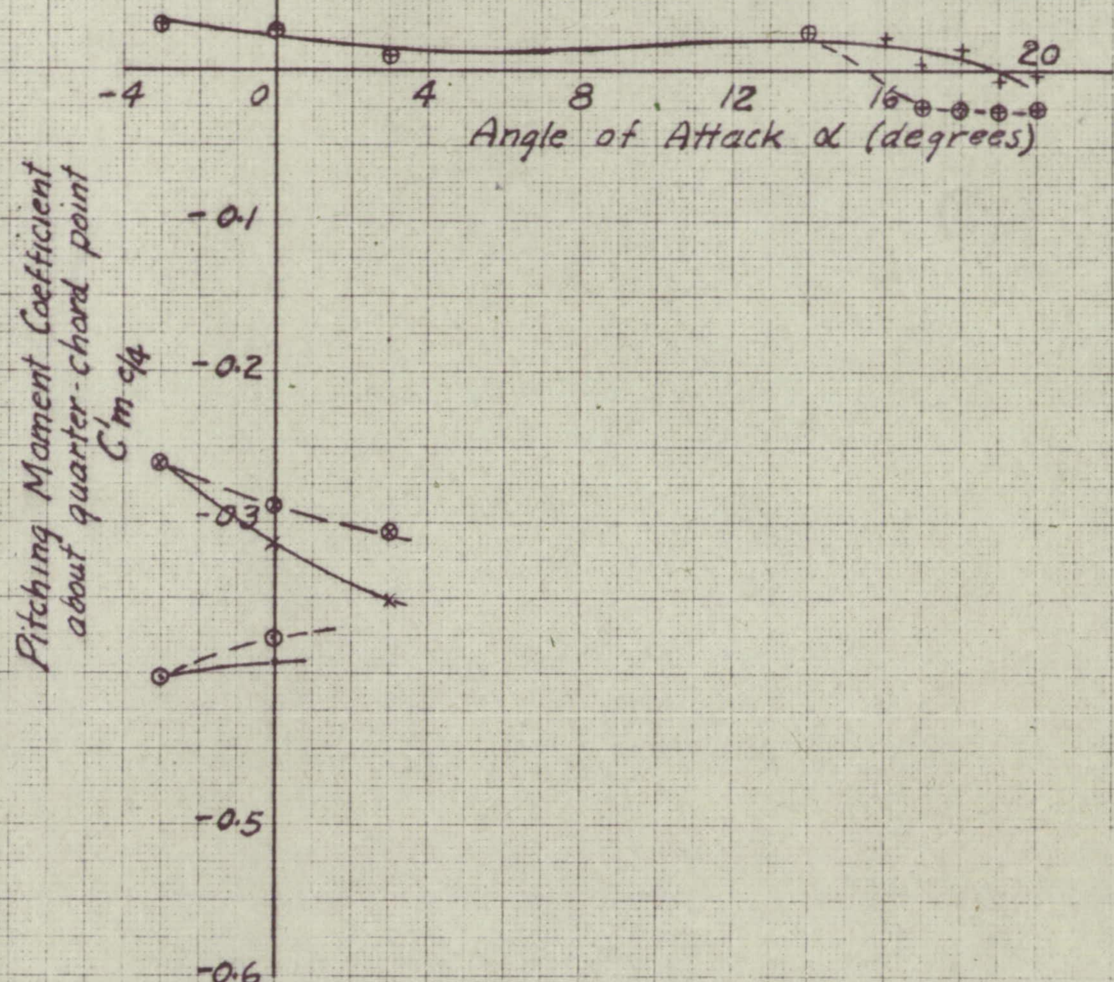

Fig. 10

Pitching moment coefficients about quarter-chord point $C'_{m_{c/4}}$ measured in free air and over ground board for 0.6 chord ground clearance.

0° flap setting, free air ——+——
over ground board ---⊕---
45° flap setting, free air ——×——
over ground board ---⊗---
60° flap setting, free air ——•——
over ground board ---⊙---

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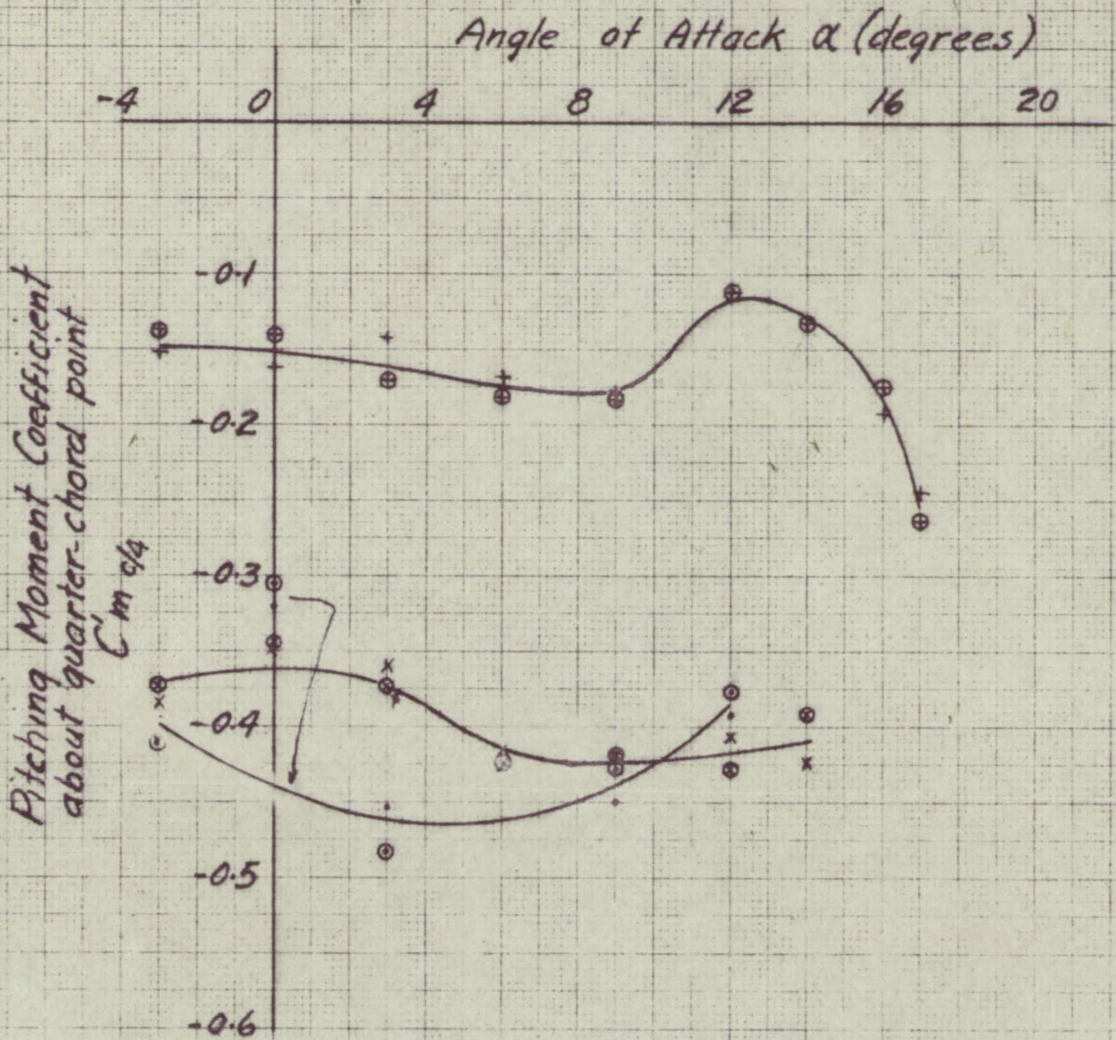

Fig. 11
Pitching moment coefficients about quarter-chord point $C'_{m\,c/4}$ measured in free air and over ground board at 0.8 chord ground clearance

0° flap setting, free air ——+——
over ground board – – –⊕– – –
45° flap setting, free air ——x——
over ground board – – –⊗– – –
60° flap setting, free air ——·——
over ground board – – –⊙– – –

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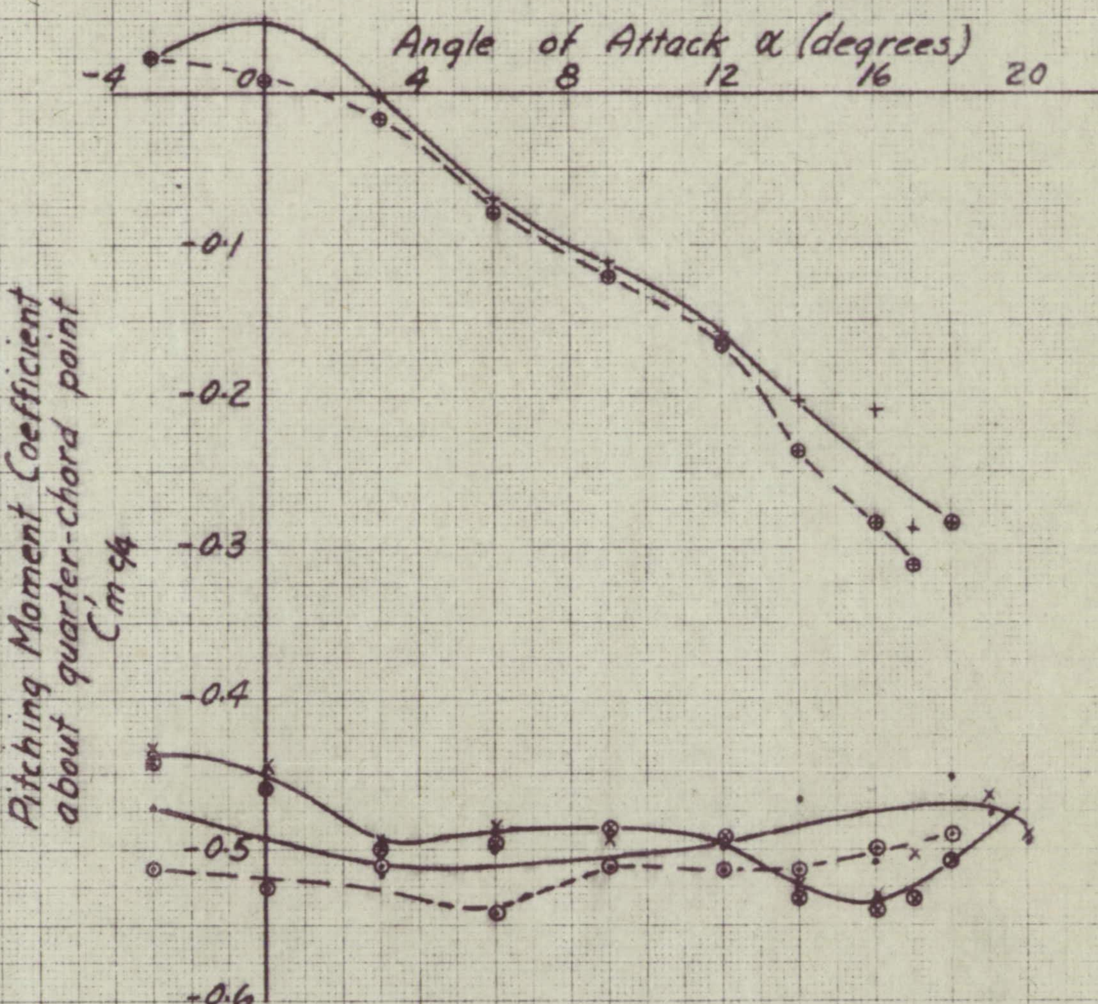

Fig. 12
Pitching moment coefficients about quarter-chord point $C'_{m_{c/4}}$ measured in free air and over ground board for 1.2 chord ground clearance

0° flap setting, free air
over ground board
45° flap setting, free air
over ground board
60° flap setting, free air
over ground board

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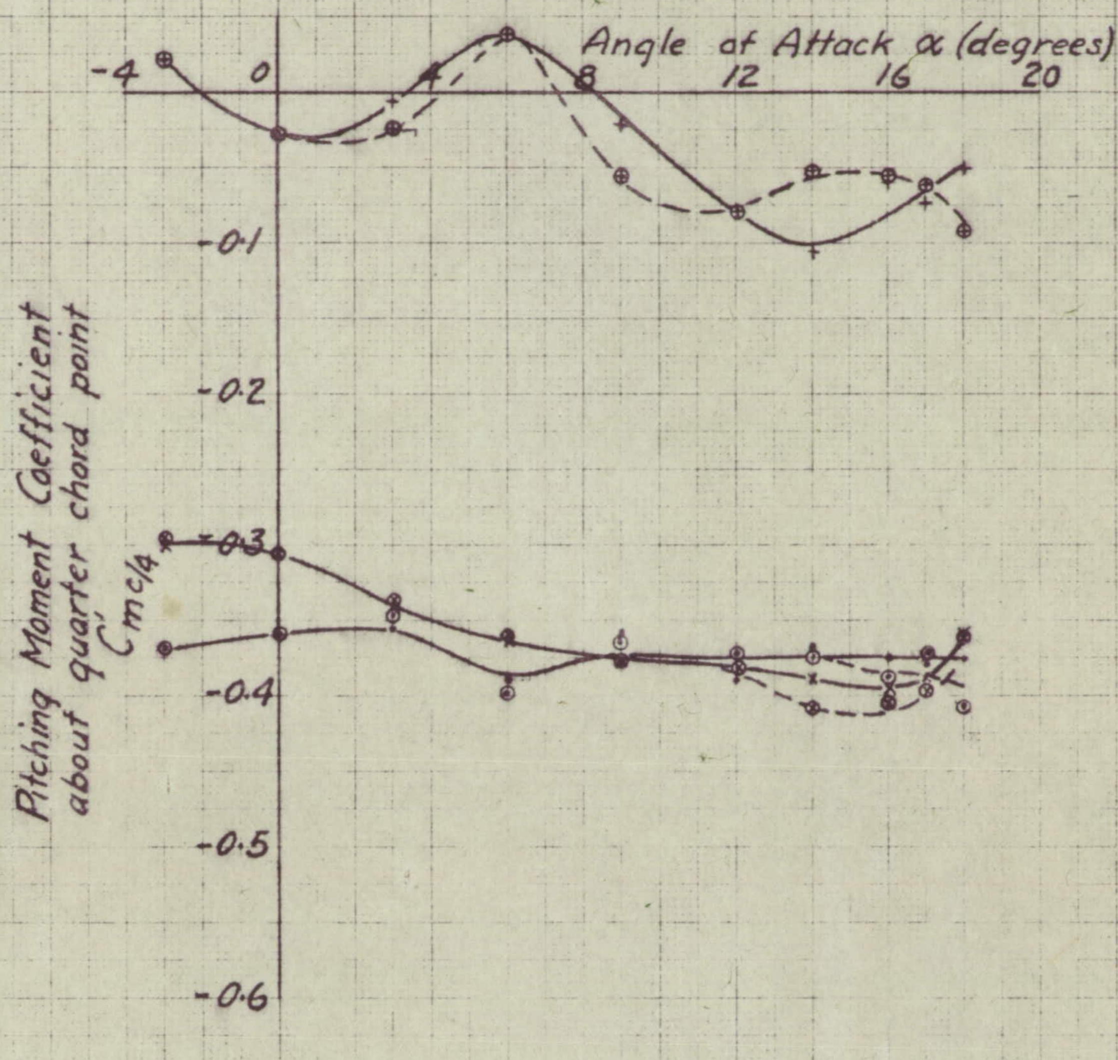

Fig. 13

Pitching moment coefficients about quarter-chord point $C'_{m_{c/4}}$ measured in free air and over ground board for 1·6 chord ground clearance.

0° flap setting, free air ——+——
over ground board — —⊕— —
45° flap setting, free air ——×——
over ground board – – –⊗– – –
60° flap setting, free air ——·——
over ground board – – –⊙– – –